it is possible to make the length of the material equal to integer multiples of each half wavelength of the three waves, if the dielectric constant does not vary with the frequency. (Since the dielectric constant can be changed by dc bias voltage, the wavelength can be adjusted by dc bias. Consequently, the length of the material can be made equal to the multiples of the half wavelengths of all three frequencies.)

Suppose that a TEM wave is applied into a ferroelectric substance both of whose surfaces facing each other are parallel and are perpendicular to the propagating direction of the wave. The ratio, t, of the amplitude of the wave which passes through the substance and of the incidental wave is easily obtained.

$$|t| = 4\xi e^{-\alpha D}/\sqrt{(1+\xi)^4 - 2(1-\xi^2)^2 e^{-2\alpha D}\cos\theta + (1-\xi)^4 e^{-4\alpha D}}, \qquad (3)$$

where ξ is $\sqrt{\epsilon_{air}/\epsilon_{substance}}$, D is the length of the substance, α is the attenuation constant of the substance, and $\theta = 4\pi D/\lambda$. λ is a wavelength in the substance.

On the other hand, the gain of the parametric amplification with respect to the signal wave in the substance is obtained from a modified theory of Tien and Suhl.[9] As for the attenuation constant of the signal wave, α, in (3) should be expressed by

$$\alpha = \alpha_1 - \alpha_g, \qquad (4)$$

where α_1 is the true attenuation constant of the substance, and α_g is the gain and is expressed as follows:

$$\alpha_g = \frac{1}{4}\sqrt{\beta_s\beta_i}\,\frac{|\epsilon_p^0|}{\epsilon_0}, \qquad (5)$$

where β_s and β_i are phase constants of signal wave and idling wave, respectively, ϵ_0 is the constant part of the dielectric constant, and ϵ_p^0 is the amplitude of the alternating part of the dielectric constant caused by pumping wave. When $D = n\lambda/2$, (3) is simplified, and

$$|t| = 4\xi e^{-\alpha D}/\{(1+\xi)^2 - (1-\xi)^2 e^{-2\alpha D}\}. \qquad (6)$$

These results show that amplification can be obtained when $\alpha_1 < \alpha_g$, where $|t|$ is the amplification of the amplifier. The maximum amplification is obtained when

$$e^{-\alpha D} = \frac{1+\xi}{1-\xi}. \qquad (7)$$

In the practical design of the amplifier, the following must be considered:

1) *Roughness of the surface of the ferroelectric substance.* In order to make the length of the ferroelectric substance equal to multiples of the half wavelength, opposite faces perpendicular to the wave must be exactly parallel to each other. The roughness of these surfaces decreases the amplification. There are two possible effects. One of the effects is such that the roughness affects $|t|$ directly. The other is that the roughness decreases the amplitude of the pump wave in the substance and consequently decreases the gain α_g.

2) *Change of the dielectric constant with the microwave frequency.* Amplification was calculated with the assumption that the dielectric constant was independent of frequency. When the dielectric constant varies with the frequency, two undesirable effects take place. One is that the wavelength in the substance depends on the dielectric constant, so that similar effects as that of roughness occur. The other is that the gain α_g is decreased by the change of the dielectric constant with frequency. These were analytically calculated, but only numerical results will be shown.

Finally, some practical examples will be presented. First, let us consider the case when the nonlinear material is barium (73 per cent)-strontium (27 per cent)-titanate ceramics, which was measured by Davis, and Rubin at 3000 mc.[7]

Material ($BaTiO_3$, 73 per cent; $SrTiO_3$, 27 per cent) at 23°C with 5 kv/cm bias

Dielectric constant	about 3600
Dielectric loss	tan $\delta = 0.1$
	$\lambda_0\alpha_1 = 18.8$ nepers
Nonlinearity	ϵ_p^0/ϵ_0 per field strength $= 7$ per cent/(kv/cm)

Amplifier

Frequency			
signal	3000 mc		
idling	3000 mc or	6000 mc	
pumping	6000 mc	9000 mc	
Dimension			
thickness	0.1 mm		
length	0.83 mm ($=\lambda_s/2$)		
width	5 mm		

Results

Pumping voltage	
at minimum gain	2 kv/cm
at 20-db gain	2.4 kv/cm
at maximum gain	2.5 kv/cm
Pumping power	
at 20-db gain	4.7 kw at peak power

The roughness of surface must be within ±0.01 mm.[10]

The change of the dielectric constant at the pumping frequency and at the signal frequency must be within 2.2 per cent.[10]

These results show that

1) material must be extremely small;
2) very precise work is necessary to fabricate the material;
3) rather high pumping power is necessary.

These undesirable facts are caused by the high dielectric constant and high dielectric loss of the material.

Next, let us consider the case when a new material, whose characteristic is shown in the following table, is used as a nonlinear substance. This material was originally proposed by Cassedy.[5] It is believed, however, that the material could not be easily prepared by suspending $(BaSr)TiO_3$ in a nonpolar binder as Cassedy proposed, because of the difference in the dielectric constant of $(BaSr)TiO_3$ and the nonpolar binder. It may be possible to obtain the desired material by mixing certain materials with $BaTiO_3$.

Material

Dielectric constant	about 100
Dielectric loss	tan $\delta = 0.01$
	$\lambda_0\alpha_1 = 0.31$ neper
Nonlinearity	ϵ_p^0/ϵ_0 per field strength $= 7/$(kv/cm)

Amplifier

Frequency	same as that for $(BaSr)TiO_3$
Dimension of material	
thickness	0.1 mm
length	5 mm ($=\lambda_s/2$)
width	5 mm

Results

Pumping voltage	
at minimum gain	330 volts/cm
at 20-db gain	420 volts/cm
at maximum gain	460 volts/cm
Pumping power	
at 20-db gain	1.5 watts at peak power

The roughness of surface must be within ±0.3 mm.[10]

The change in the dielectric constant at the pumping frequency and the signal frequency must be within 13 per cent.[10]

It is concluded that the new material would be suitable for an amplifier. The physical size of such material would not be too small for fabrication, and precise work will not be required. The pumping power would be only perhaps one to two watts.

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YOSHIMASA AOKI
Osaka City University
Osaka, Japan

[9] P. K. Tien and H. Suhl, "A traveling-wave ferromagnetic amplifier," PROC. IRE, vol. 46, pp. 700–706; April, 1958.

[10] In this case, the amplification coefficient $|t|$ does not decrease below half of that of the ideal case.

A Broad-Band Ferrite Reflective Switch*

Several types of reflective ferrite switches have recently been described in the literature.[1,2] These have typically made use either of the Faraday rotation effect or of a waveguide cutoff induced by a transversely-magnetized ferrite slab. A different and very simple type of switch, which exhibits similar reflective behavior, may also be obtained by the use of a short section of heavily-loaded (or filled) coax, stripline, or waveguide. Application of an axial magnetic field

* Received by the PGMTT, May 5, 1960.

[1] R. F. Soohoo, "A ferrite cutoff switch," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-7, pp. 332–336; July, 1959.

[2] G. S. Uebele, "High-speed, ferrite microwave switch," 1957 IRE NATIONAL CONVENTION RECORD, pt. 1, pp. 227–234.

of sufficient magnitude can cause the effective permeability of the ferrite to approach zero and under this condition electromagnetic waves are strongly reflected by the ferrite, producing a cutoff effect that is relatively independent of the type of propagating structure. This type of device possesses the advantages of being small in size and broad-band. It requires only a moderate magnetic field, whose magnitude can vary over a wide range. Furthermore, it may be used over much of the UHF and SHF frequency regions by choosing a ferrite with the proper saturation magnetization ($4\pi M_s$).

Some typical measured data are shown in Figs. 1 and 2 for a short section of shielded stripline filled with Trans-Tech TT 414 ($4\pi M_s=600$ gauss). This structure does not represent an optimized design; rather, it is the simplest arrangement. The ferrite pieces are rectangular in shape with blunt ends (*i.e.*, no tapering or chamfering). The ends of the stripline section contain conventional ("straight-through") transitions to type *N* coaxial connectors. From Figs. 1 and 2 it may be seen that an attenuation greater than 45 db and a VSWR greater than 18 may be obtained over the frequency region from 2000 to 2800 mc if a magnetic field of 400 oersteds is applied during the OFF state. If only narrow-band operation near 2000 mc is desired, an insertion loss of 40 db and a VSWR of 23 may be achieved with a field of less than 150 oersteds. The axial magnetic field is provided by passing a current through a coil wrapped directly on the stripline. Since the structure is extremely short and also very small in cross section, relatively rapid switching is possible, particularly if narrow-band operation is permissible. Switching times of the order of ten microseconds can be achieved for moderate switching powers.

By using materials with higher saturation magnetizations, similar characteristics may be obtained at higher frequencies. The same stripline ($2\frac{1}{4}$ inches long) filled with a ferrite whose $4\pi M_s$ value was 1500 gauss gave results at *C* band comparable to those in Figs. 1 and 2. Waveguide heavily loaded

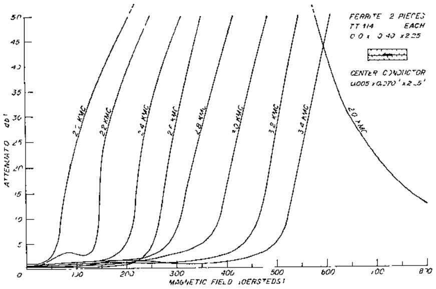

Fig. 1—Attenuation characteristics of stripline ferrite switch at *S* band.

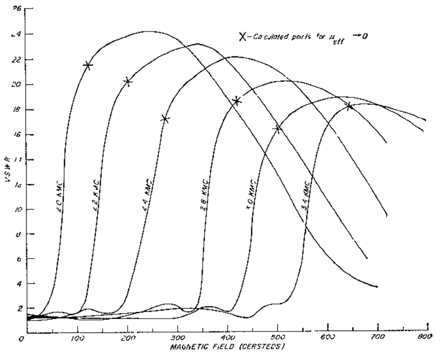

Fig. 2—VSWR characteristics of stripline ferrite switch at *S* band.

with this same ferrite was investigated as a possible configuration for a *C*-band switch. The waveguide was of reduced size (0.17 inch by 0.9 inch I.D.) and was filled with polystyrene to reduce the waveguide cutoff frequency well below the operating range of 5 to 6 kmc. A centrally-located piece of ferrite 0.16 inch high and about half as wide as the guide gave switching action that was nearly comparable to that obtained with the stripline; however, about 50 per cent more length of ferrite was needed in the waveguide configuration.

It has been shown[3] that the effective permeability of axially-magnetized ferrite slabs loading a stripline as shown in Fig. 1 is given by

$$\mu_{\text{eff}} = \frac{\mu^2 - \kappa^2}{\mu} \quad (1)$$

where μ and κ are the diagonal and off-diagonal terms of the well-known permeability tensor. If the μ and κ are evaluated in terms of the magnetization, $4\pi M$, the applied field H, the frequency ν, and the gyromagnetic ratio γ, (1) becomes

$$\mu_{\text{eff}} = \frac{\nu^2 - \gamma^2(H^2 + 8\pi MH + 16\pi^2M^2)}{\nu^2 - \gamma^2H(H + 4\pi M)}. \quad (2)$$

At $H=0$, M is also zero and $\mu_{\text{eff}} \approx 1$. As H increases, $4\pi M \rightarrow 4\pi M_s$ and both the numerator and denominator of (2) decrease. The numerator, however, decreases faster and $\mu_{\text{eff}} \rightarrow 0$ at some higher value of H. These $\mu_{\text{eff}}=0$ points as calculated from (2) (with $4\pi M_s=600$ gauss and $\gamma=2.74$ mc/gauss) are shown on the experimental curves of Fig. 2.

At present, a range of values of $4\pi M_s$ from 400 to 5000 gauss and of γ from 1.5 to 3.7 mc/gauss can be obtained from commercially available ferrites. With an arbitrary limitation of 800 oersteds on the maximum switching field, available ferrites limit the usefulness of this type of switch to the range from 500 to 11,000 mc. Use of fields as high as 1000 oersteds extends the upper frequency limit to 12,300 mc.

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C. M. Johnson
Emerson Res. Labs.
Silver Spring, Md.
Formerly at Electronic Communications, Inc.
Timonium, Md.
J. C. Wiltse
Electronic Communications, Inc.
Timonium, Md.

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